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A TRAPEZOIDAL FLUME FOR GAGING MOUNTAIN STREAMS

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Rocky Mountain Forest and Range Experiment Station*

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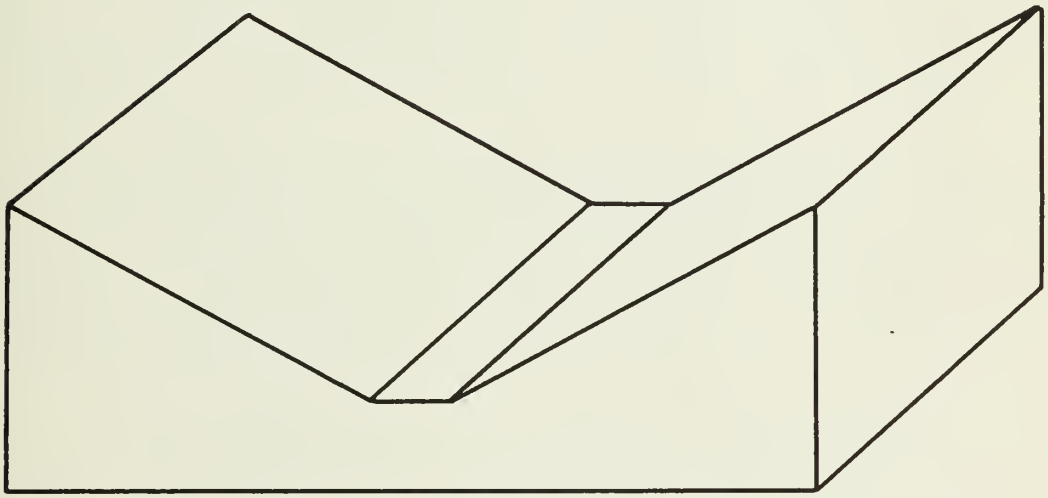

*Maintained at Fort Collins, Colorado, in cooperation with Colorado A&M College

A TRAPEZOIDAL FLUME FOR GAGING MOUNTAIN STREAMS

By
B. C. Goodell, Forester[1]

THE PROBLEM

Watershed management research in mountainous terrain often requires the accurate gaging of mountain streams with high channel gradients. A desirable gaging device for such streams is one which satisfies the following criteria: (1) is susceptible to accurate flow rating; (2) causes a minimum of channel disturbance; (3) readily passes all sediment; and (4) is of simple design and frugal of material. The last is important because desirable mountain stream-gaging sites frequently may be accessible only by pack horse and foot travel. Durable construction materials must then be kept to a minimum.

Various kinds of flumes and weirs have been designed and successfully used for measuring the flow in channels.[2] Usually they have been designed and used with specific purposes in mind. Thus sharp-crested weirs are well suited for the measurement of streams with low gradient where sediment transportation is low and adequate stilling ponds can be constructed and maintained. Conversely, they are unsuited for mountain streams of high gradient and heavy bedload movement.

Both the Parshall[3] and San Dimas[2] flumes have proven satisfactory for measuring stream flow under a variety of conditions of channel gradient and sediment transportation. The latter was specifically designed for gaging steep mountain streams transporting heavy sediment loads and has been especially successful for that purpose. However, both of these flumes are rather complicated in design and construction requirements and are expensive to build in inaccessible locations.

Earlier experiments with simple trapezoidal flumes having side-wall slopes of approximately 75° from the horizontal, conical transitions, and floor widths of 0.5, 1.0, and 2.0 feet, resulted in unstable flow conditions. Surface waves appeared in all flume widths and at all stages to the extent that the design was considered unsatisfactory. The unstable flow conditions

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1/ Division of Forest Influences Research, Rocky Mountain Forest and Range Experiment Station. Grateful acknowledgement is made to the Colorado A. & M College for the use of the Hydraulic Laboratory facilities; to Mr. Maxwell Parshall, assistant professor of civil engineering, and to H. G. Wilm, formerly of the Division of Forest Influences Research.

2/ Wilm, H. G., Cotton, John S., and Storey, H. C. 1938. Measurement of debris-laden stream flow with critical depth flumes. Trans. Amer. Soc. Civ. Engin. 103: 137.

3/ Parshall, R. L. 1941. Measuring water in irrigation channels. U. S. Dept. Agr. Farmers' Bul. 1683.

were partially attributed to the insufficient radius on the transition section. The high ratio of side-wall slope to channel slope may also have contributed by favoring the formation of cross-channel flow lines.

During 1942 a stream-gaging station partially meeting the above criteria was constructed on East St. Louis Creek of the Fraser Experimental Forest in Colorado (fig.1). The installation as originally planned was a simple trapezoidal flume with a floor 1 foot in width, side-wall slopes to fit the channel bed (about 15°), an entrance transition of 4-inch radius of curvature, a downstream gradient of 3 percent less than that of the natural channel, a channel length of 4 feet, and a piezometer opening midway of the flume length. During installation the design was altered and the flume floor converted to a "slot" 1.4 feet wide with 0.80-foot vertical walls joining the sloping side-walls (fig. 1).

The flume as installed is satisfactory for low and high flows, but is limited for the measurement of intermediate stages. As the capacity of the slot entrance is exceeded, there is a range of depths at which convergency of the flow extends part way along the side-wall slopes and portions of the flow enter the slot at or below the piezometer opening. Under these conditions the flow at the piezometer opening is variable and the stage-discharge relationship is not subject to reliable determination. The slot feature is thus undesirable.

Also from observations of the behavior of the East St. Louis flume it appeared that more accurate stream-flow measurements would result from (1) the lengthening the flume, (2) the placing the piezometer opening downstream from the midlength point, and (3) increasing the radius of curvature of the transition section.

THE EXPERIMENT

The objective of the present study was to develop a simple but adequate design for a mountain stream-gaging station. To be satisfactory the design had to meet the criteria of accurate stream-flow measurement, minimum channel disturbance, complete sediment passage, and simplicity of design and construction. Specifically, the study tested a flume incorporating the desirable changes in the East St. Louis flume, and tested the range of side-wall and channel slopes over which such a trapezoidal flume would likely give satisfactory flow characteristics. Knowledge of this range is necessary in order that the criterion of minimum channel disturbance may be met.

The tests were conducted in the hydraulic laboratory of Colorado A & M College. A model flume was constructed on a one-third scale of the original design of the East St. Louis flume extended to 8 feet in length. The model dimensions became 4-inch floor width, and a 32-inch channel length. The radius of the cylinder quadrant transition was increased to 24 inches in the prototype or 8 inches in the model. Provisions were made for varying the side-wall slopes through settings of approximately 15, 25, and 35 degrees from horizontal and for setting the channel slope at about 2, 4, and 6 percent. The plywood floor and walls were covered with muslin and varnished to provide a seal at the hinged joints and also to

Figure 1. A trapezoidal flume used to gage stream flow of East St. Louis Creek, Fraser Experimental Forest. Low flow is checked with a velocity head rod.

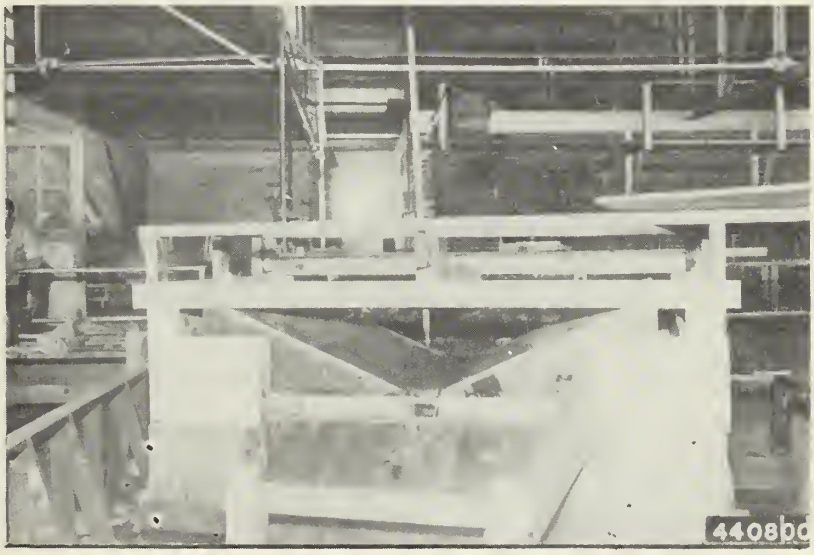

Figure 2. Trapezoidal flume model ready for operation. Side-wall slopes 25° and channel slope 4 percent. Point gage over the center of the flume.

simulate a surface of finished concrete. The approach channel was given a fixed slope of 6 percent and filled to flume floor level with gravel which was given a concave cross section to approximate a natural stream channel (figs. 2 and 3).

Since rating of small flumes can be done accurately and efficiently in the field by use of the velocity head rod[4] no precise attempt at rating the laboratory model was made. However, to observe the shape of the depth-discharge curve and conformance of individual points, the approach flow was measured through a 90° V-notch sharp-crested weir. Minor leakage between the weir and flume precluded accurate rating but provided the qualitative information desired for this study.

Qualitative observations of flow characteristics for different side-wall and channel slopes were the primary interest. For these observations, coordinate lines were drawn on the flume side walls to facilitate plotting of the flow boundary lines. A point gage travelling on a leveled support mounted lengthwise above the flume enabled plotting of the surface curve along the center line (fig. 2).

The range of available flow extended from 0.0 to 3.0 c.f.s. For each combination of side-wall and channel slope, discharges were varied through settings within the above range and flow lines plotted for each setting. Following the completion of the study of side-wall and channel slopes, the muslin lining of the flume was removed and observations made at one combination of slopes with the purpose of obtaining an estimate of the effects of any marked change in channel roughness.

THE RESULTS

Flume tests were made using the side-wall slopes of 16°, 25°, and 35°, and channel slopes of 2, 4, and 6 percent. (Only the 2- and 6-percent channel slopes were used with the 35° side-wall slope.) For the different amounts of flow as determined by the 90° V-notch weir above the model flume, flow-depth measurements on the flume were taken by means of a point gage. Curves were plotted to show (1) depth-discharge relationships, (2) flow boundary curves, and (3) surface profile curves for different flows. Flow depths taken at three points were plotted to determine the best point relative to flume length for the location of piezometer openings.

There follows a summary of the model flume tests for each of the three side-wall slopes.

Flume with 16° side-wall slopes

Figures 4 and 5 illustrate the unsatisfactory flow conditions of this flume. These conditions held for the channel slopes of 2, 4, and 6 percent, and for flows from 0.2 to 3.0 c.f.s. The depth-discharge curve (fig. 4) shows an inconsistent relationship between depth and discharge for the three

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4/ Wilm, H. G. and Storey, H. C. 1944. Velocity head rod calibrated for measuring stream flow. Civ. Engin. 14: 475-476.

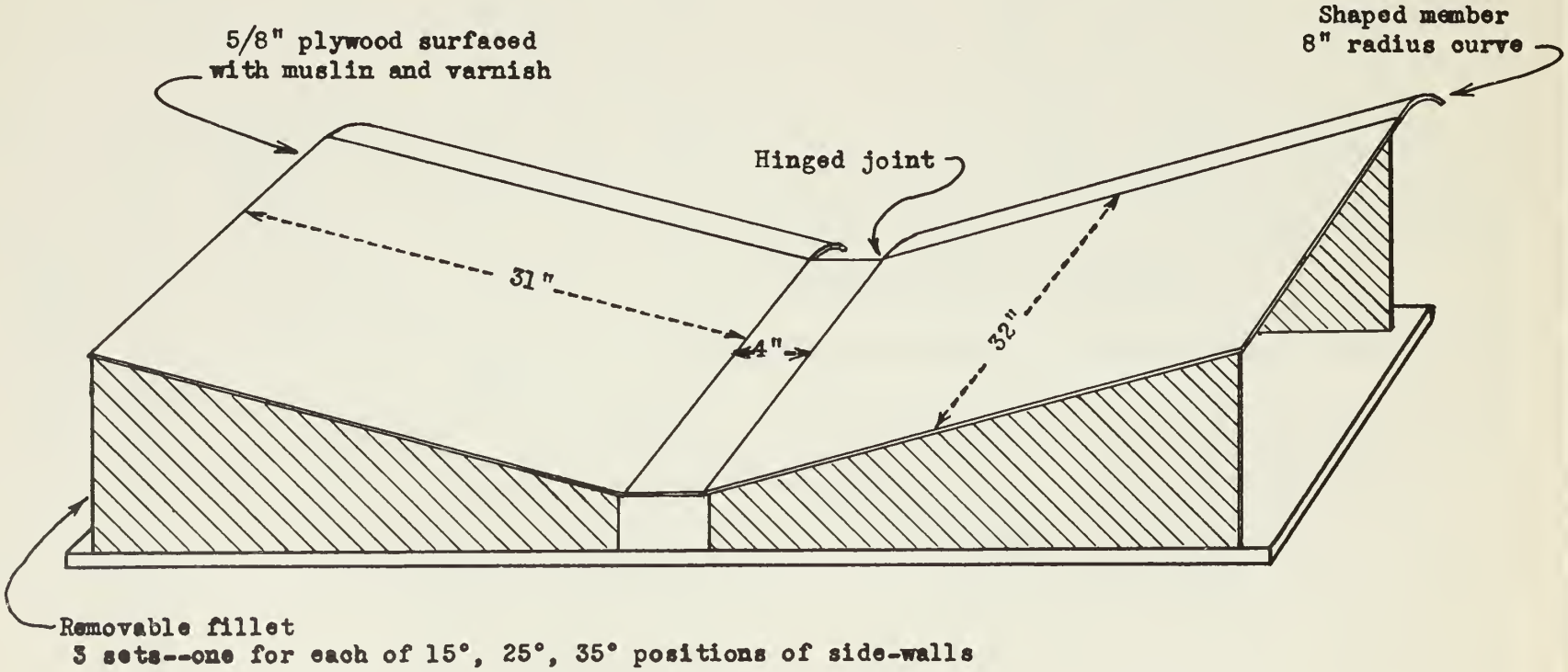

Figure 3. Design of trapezoidal flume model -- scale ratio 1:3

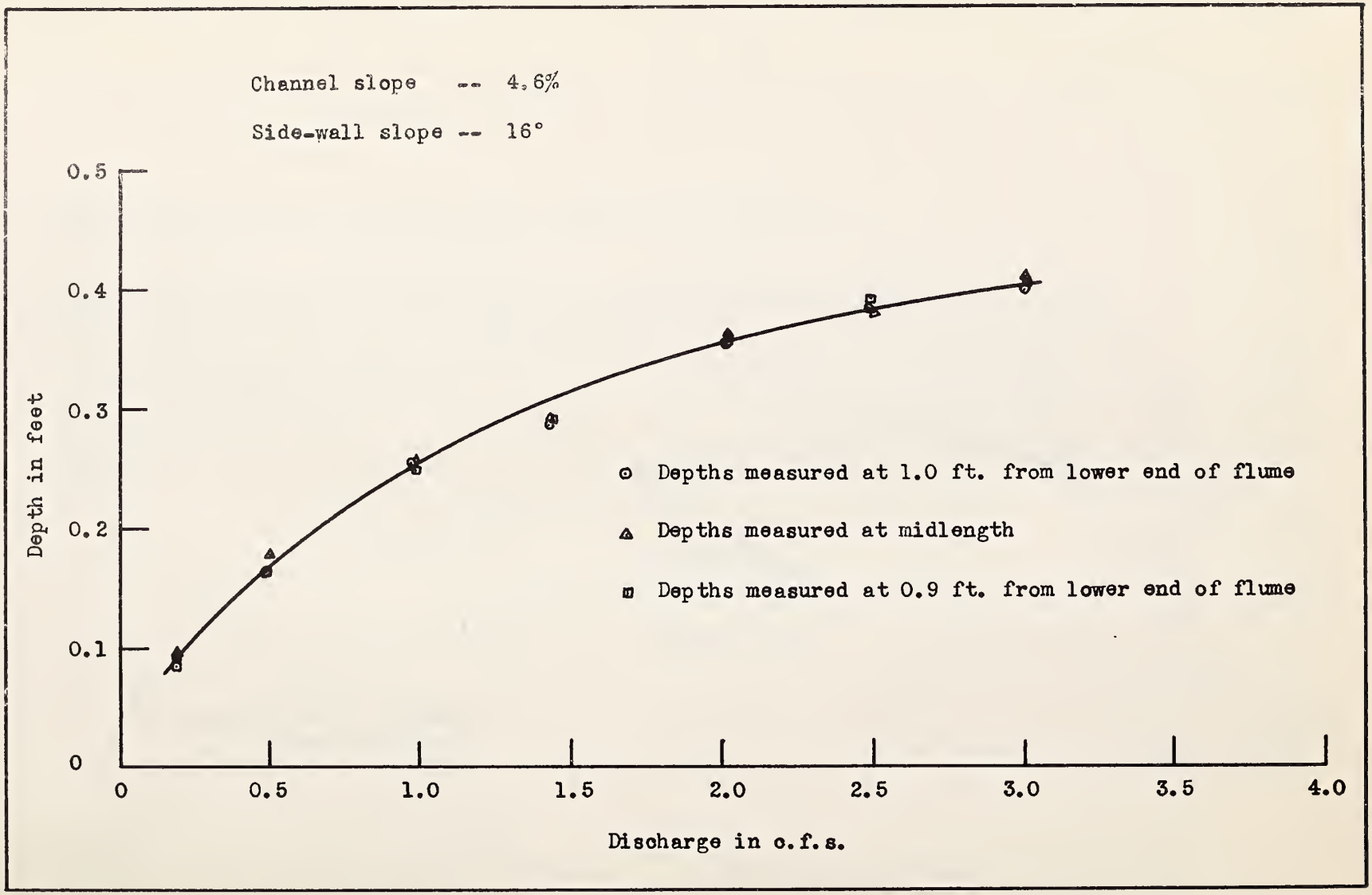

Figure 4. Depth-discharge curve -- trapezoidal flume model tests

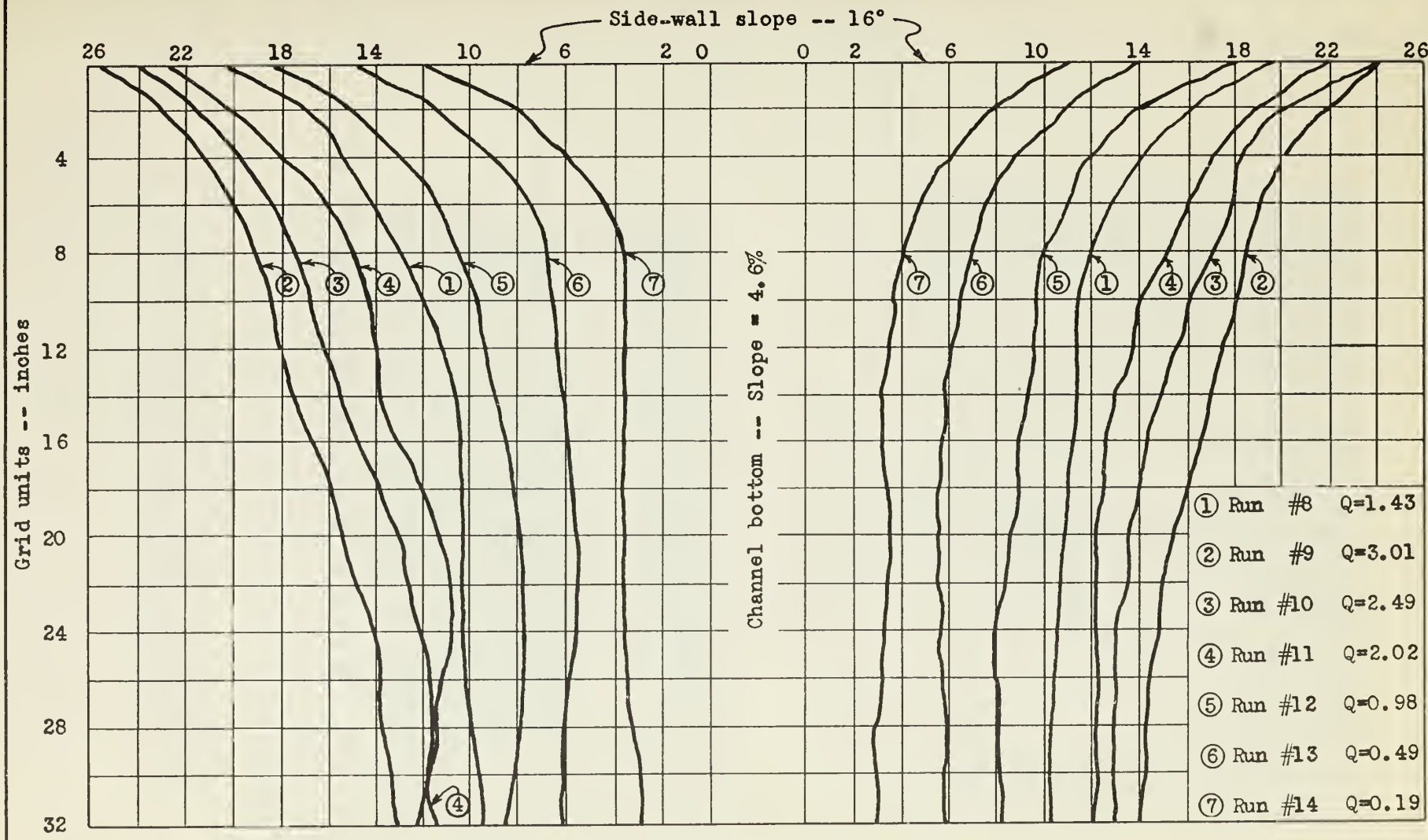

Figure 5. Flow boundary curves -- trapezoidal flume model tests

locations where depth measurements were taken. The flow boundary curves (fig.5) for higher discharges show marked convergence at and below the points of depth measurements. Accompanying this convergence was a convex water surface such that depths would be high relative to those of the parallel flow at lower stages. The boundary flow curves show irregularities throughout their lengths. This is attributed to the small contraction in flow upon entrance and to the extension of approach-flow conditions into the flume.

Flumes with 25° and 35° side-wall slopes

The behavior of these model flumes was satisfactory for all channel slopes tested. The depth-discharge curves for the flumes with 25° and 35° side-wall slopes give a smooth and consistent relationship between depth and discharge (figs. 6 and 7).

Figures 8 through 13 illustrate the flow conditions of these two flumes under different channel slopes and discharges. The flow characteristics (figs. 9 and 12) of the two flumes were reasonably uniform throughout the various combinations employed and lead to the conclusion that flumes patterned after them will give accurate measurements of the flow of mountain streams.

The depth-discharge curves (figs. 8 and 11) show that the depth values at midlength of flume (1.3 feet from lower end) and at 1.0 foot and 0.9 foot from the lower end are nearly equal in quality. Upstream from the midpoint, readings give slightly higher depth values for equal discharges as is to be expected because they are nearer the plane of critical depth and, in some cases, within the zone of convergent flow. The surface curves of figures 10 and 13, on which are indicated the computed location for Belanger's[5/] critical depths, show that in each case the points of critical depth are well upstream from the midlength of flume. These curves show smooth negative slopes for both the 25° and 35° side-wall flumes, whereas similar plottings for the 16° side-wall flume gave rough surfaces with slopes varying from negative to positive.

The final test, that with the muslin lining removed from the flume, yielded slightly irregular flow boundary curves, but depth-discharge values showed good conformity. The change in the value of "n" (roughness coefficient) did not reduce the satisfactory performance of the flume (25° side wall with 4-percent channel slope).

SUMMARY

Although this study was not sufficiently exhaustive to fix the exact optimum specifications of a flume to meet the objective criteria, it has provided the basis of judgment for specifications which should prove satisfactory

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5/ Bakhmeteff, Boris A. 1932. Hydraulics of open channels. McGraw-Hill Book Company, Inc.

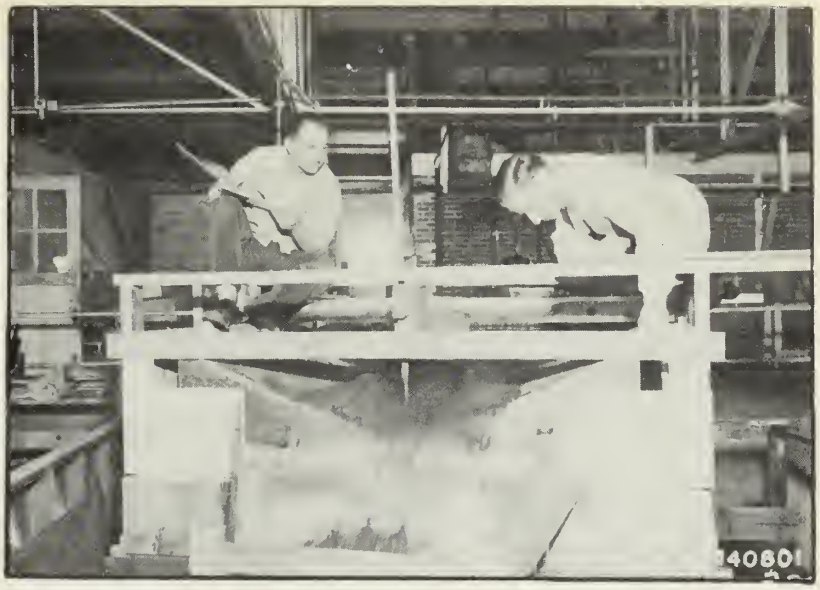

Figure 6. Flume with 25° side-wall slopes and channel slope of 4 percent. Discharge of about 2.0 c.f.s.

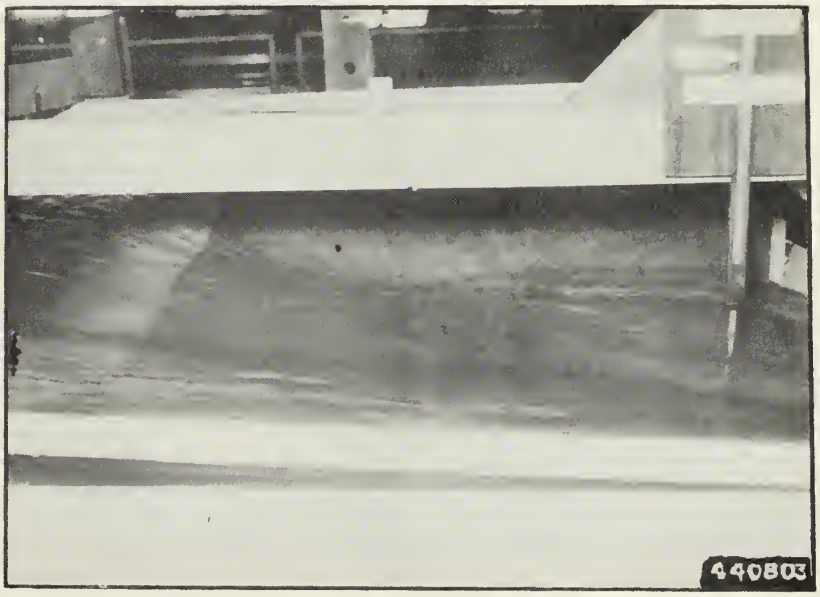

Figure 7. Flume with 25° side-wall slopes and channel slope of 4 percent showing water-surface characteristics

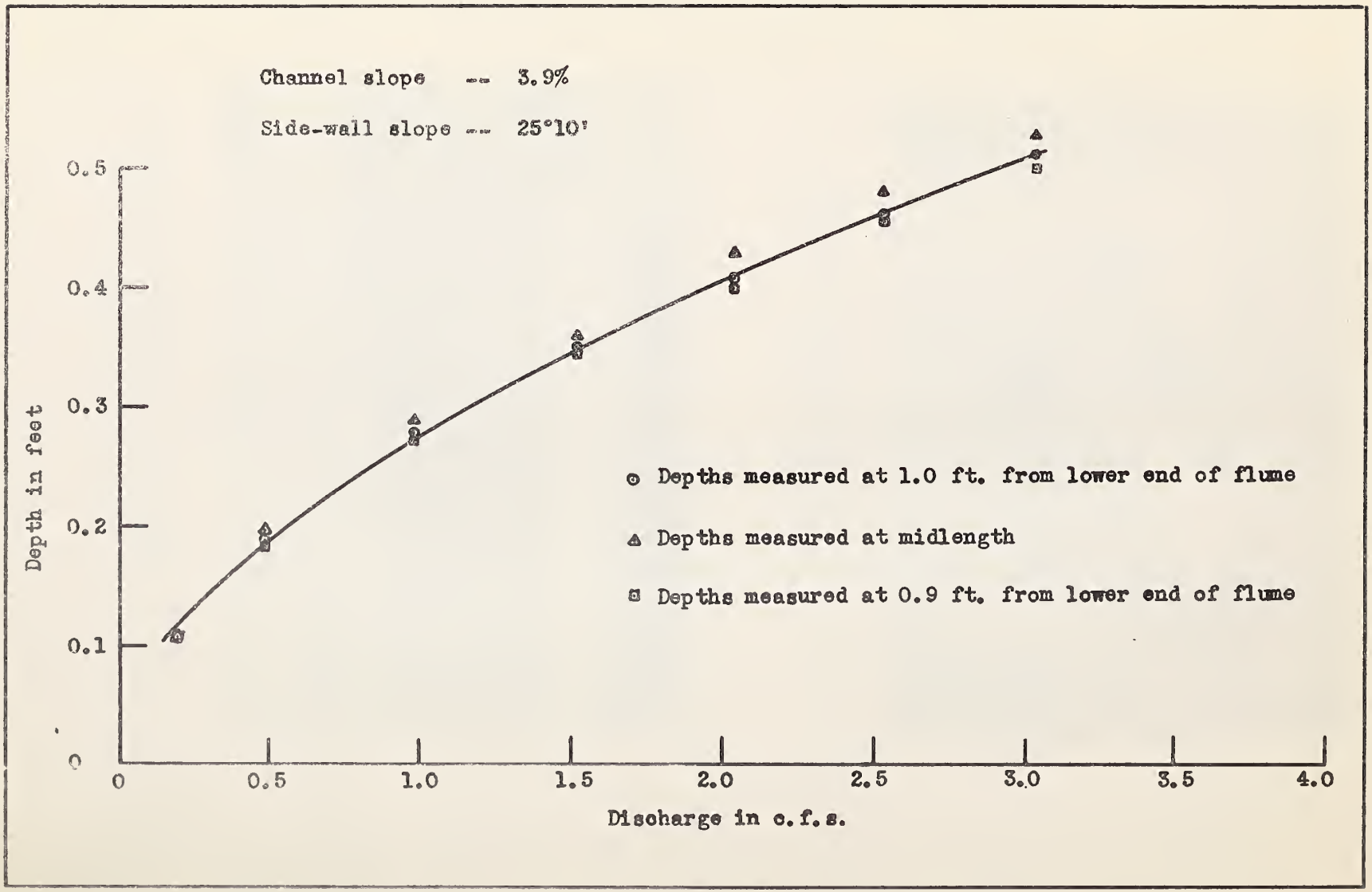

Figure 8. Depth-discharge curve -- trapezoidal flume model tests

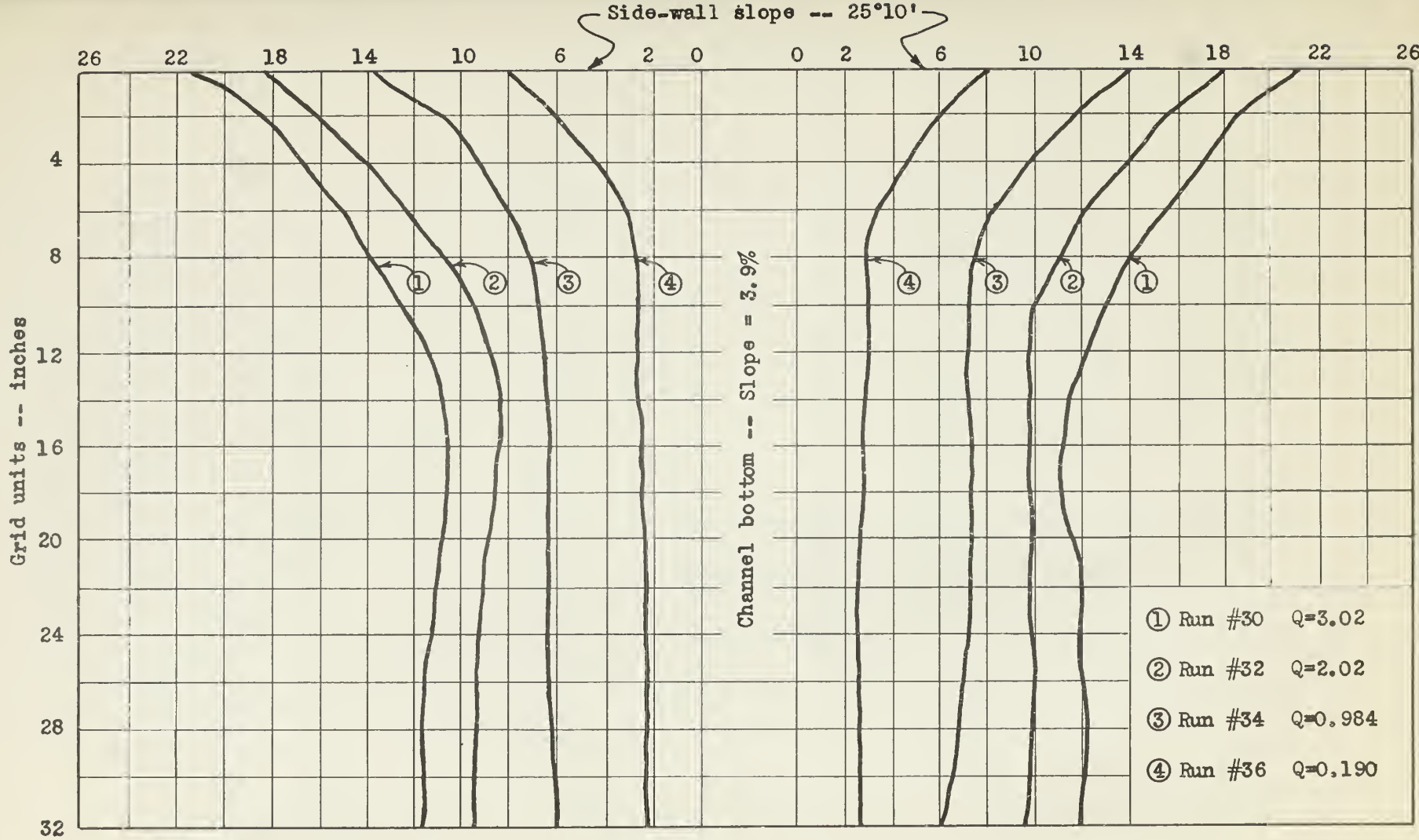

Figure 9. Flow boundary curves -- trapezoidal flume model tests

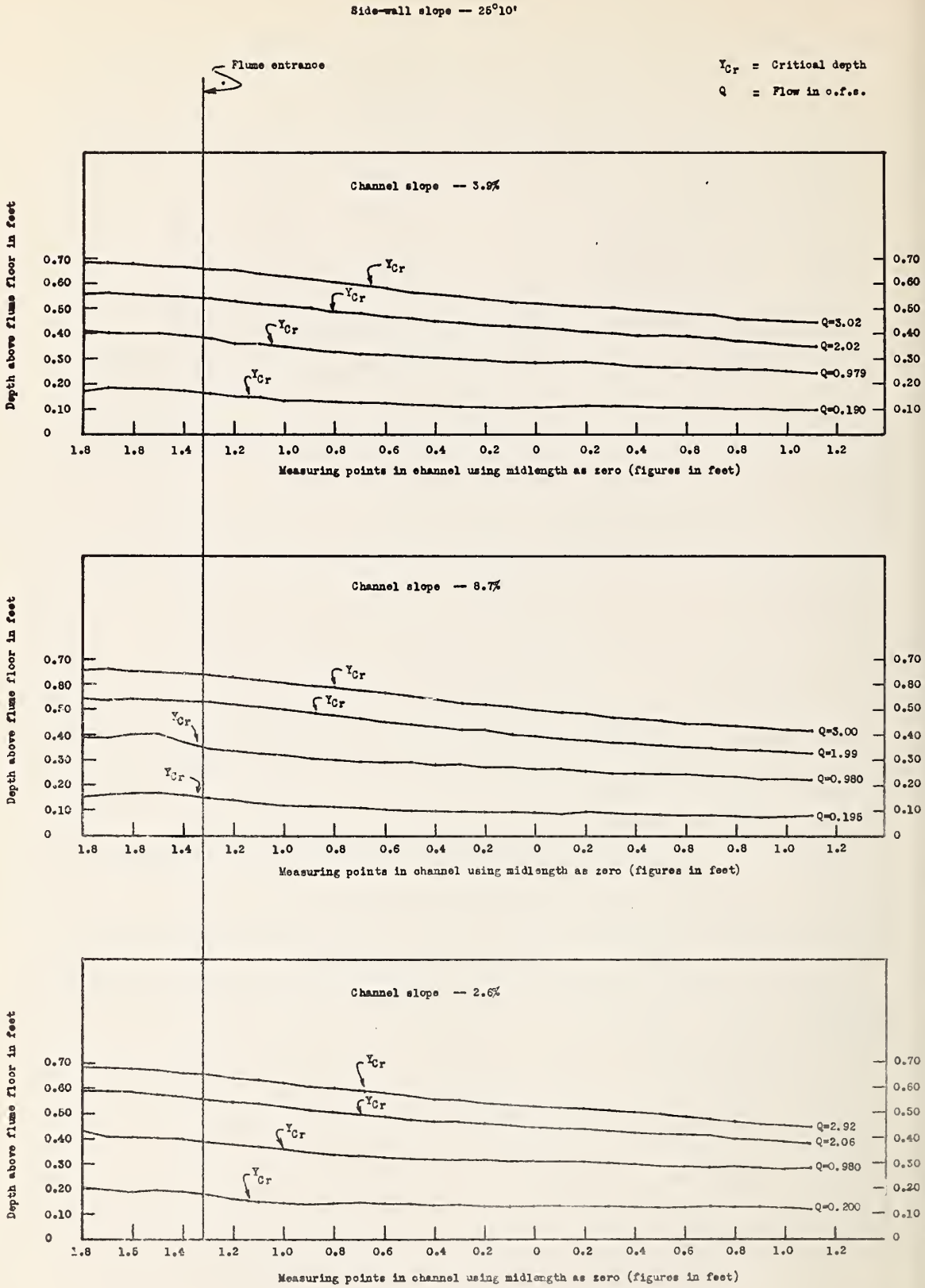

Figure 10. Surface profile curves — trapezoidal flume model tests

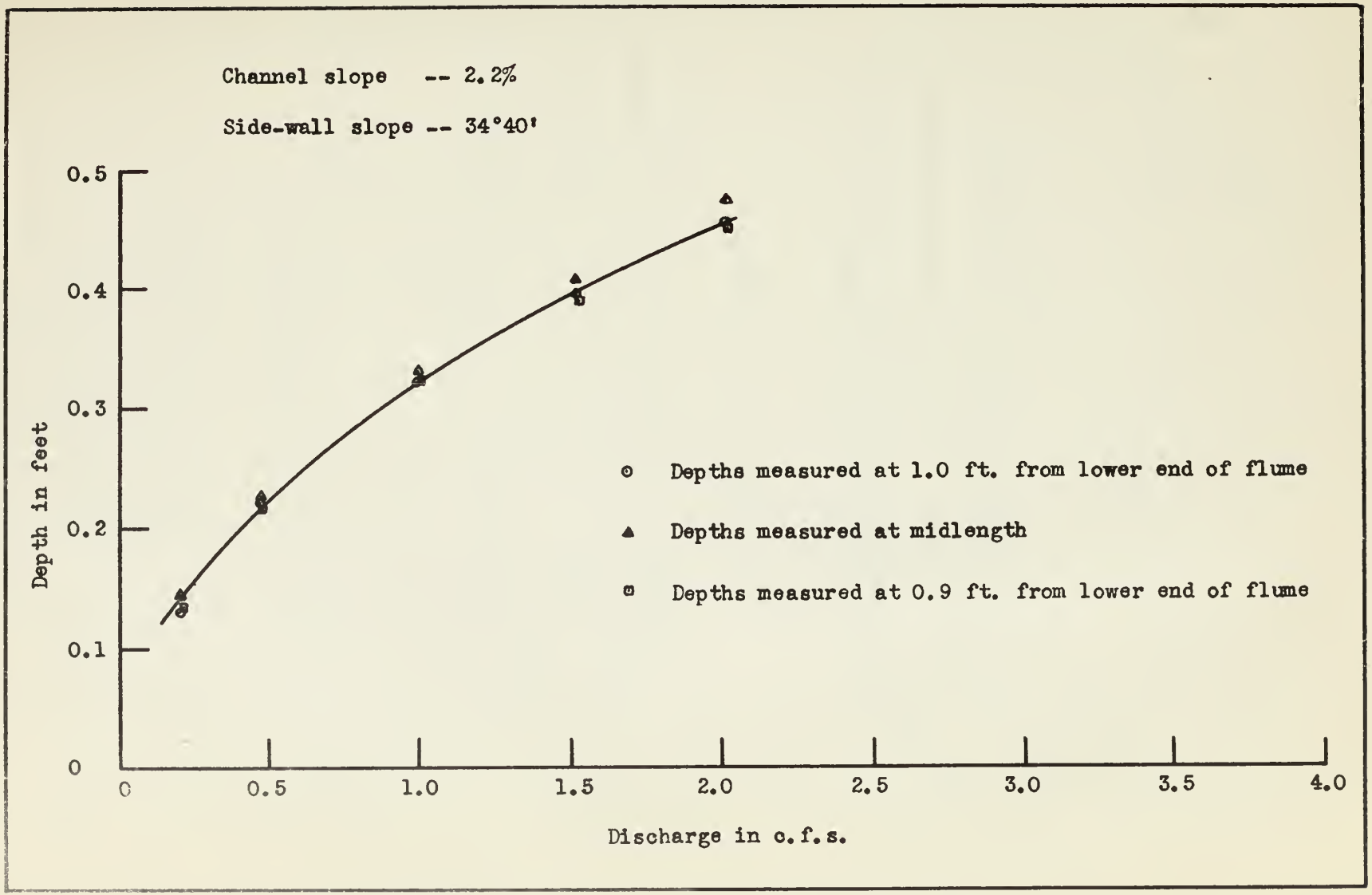

Figure 11. Depth-discharge curve -- trapezoidal flume model tests

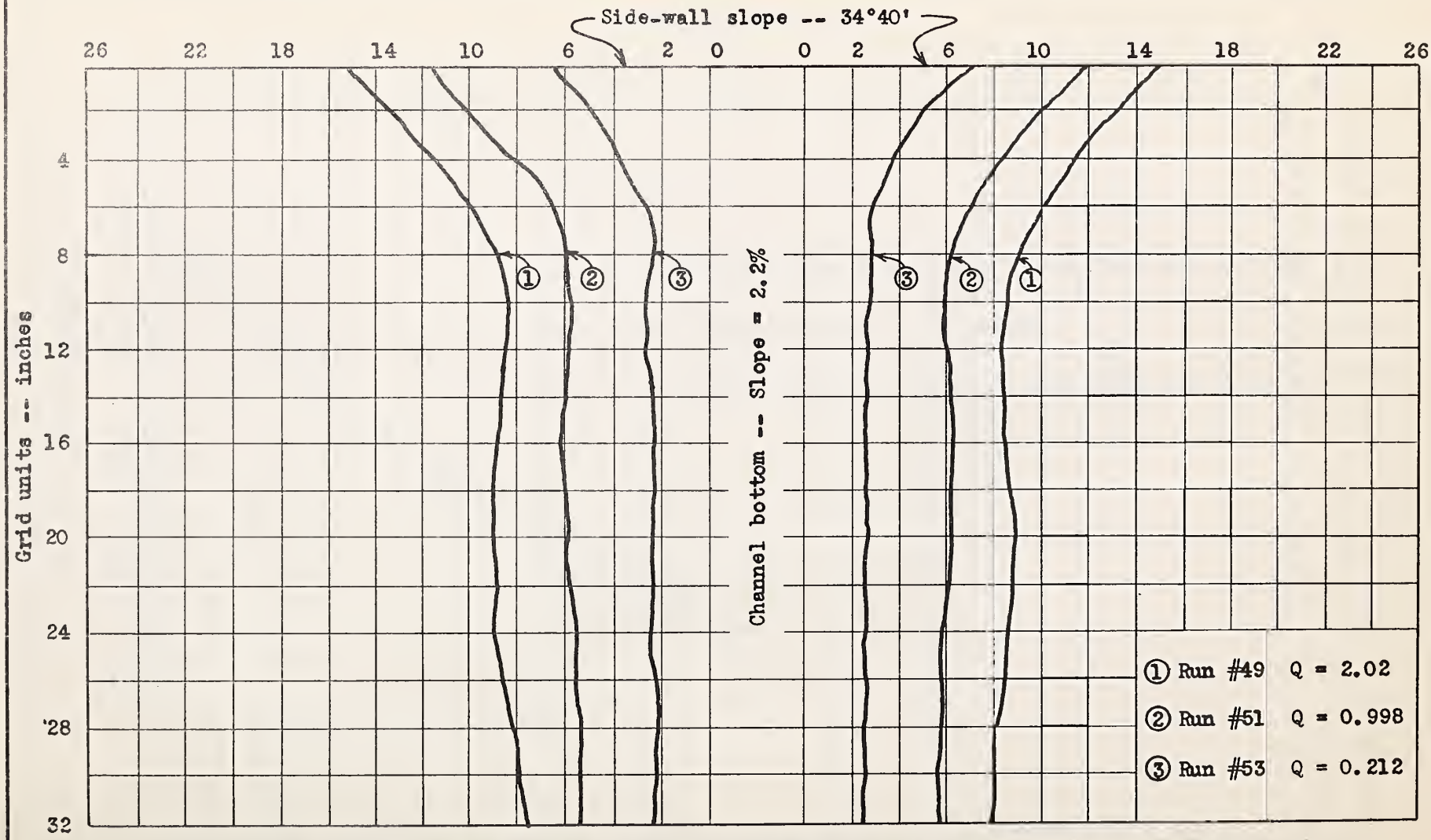

Figure 12. Flow boundary curves -- trapezoidal flume model tests

Side-wall slope — 34°40'

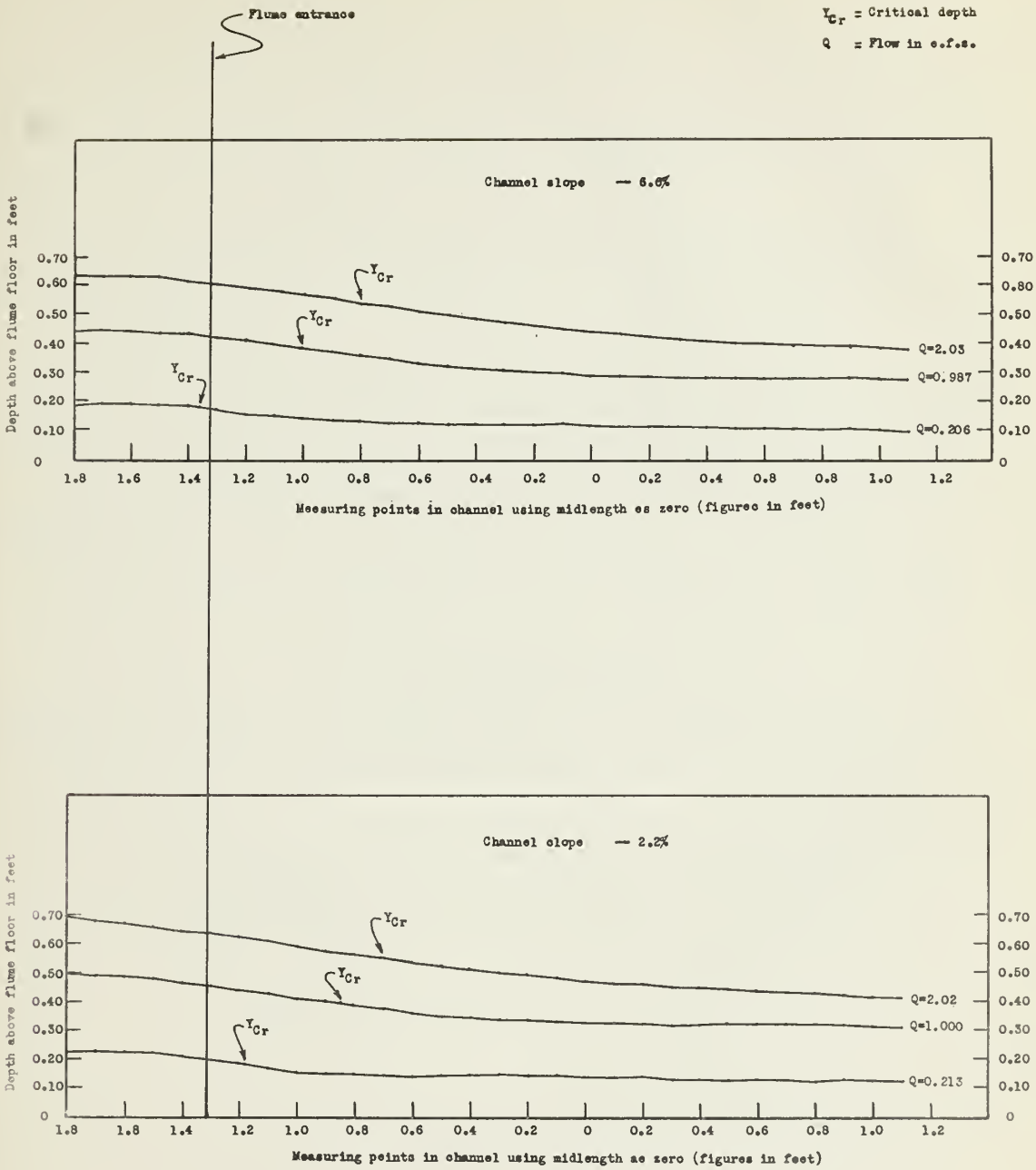

Figure 13. Surface profile curves -- trapezoidal flume model tests

The length of 32 inches (8 feet in prototype) appeared to provide sufficient length for depth readings between the curved flow of the critical depth zone and that of the draw-down curve at the exit, with allowance for translocation downstream of the point of critical depth with greater discharges. The 8-inch radius of curvature of the transition (24 inches in the prototype) was sufficient to prevent separation of flow lines and would certainly be satisfactory for all lower approach velocities. Piezometer openings in a flume of this length can be located between midlength and 0.5 foot downstream from the midpoint. Channel gradient should be sufficient to prevent sedimentation within the flume, but not so great as to lessen the sensitivity of the depth-discharge relationship. The optimum condition is probably approximated in most cases when the flume grade is made 3 percent less than that of the natural channel. Flume side-wall slopes of 25° and 35° were found to give smoother conditions of flow than 16° slopes and better conformity by individual points to depth-discharge curves. Part of the deficiencies in performance of the flume with 16° slopes is believed due to the lower ratio between side-wall slopes and channel slope. Part was almost certainly due to lesser contraction between the approach channel and the flume section. With a more concave approach channel and the accompanying condition of less contraction, more variable flow might also occur with side-wall slopes greater than 35 degrees. Such effects should not be sufficient to render the operation of the flume unsatisfactory.

FIELD ADAPTATION

The specific dimensions of a flume for any field need can be readily calculated by use of the relationship between prototype and model capacities.[6/]

6/ $Q = av$, where Q = discharge; a = cross-sectional area; v = velocity
$a = w \times h$, where w = width; h = height of flume
$v = \sqrt{2gh}$, where g = gravity; h = height of flume

Thus

$$Q_m = w \times h \sqrt{2gh}$$

Let R = ratio of lineal dimensions of prototype and model

Then

$$Q_p = R_w \times R_h \sqrt{2gRh}$$

$$= R^2(wh)\sqrt{R}\sqrt{2gh}$$

$$= R^{5/2}(wh)\sqrt{2gh}$$

Thus

$$Q_p = Q_m R^{5/2}$$ where Q_p = discharge of prototype, Q_m = discharge of model

and

$$\frac{Q_p}{Q_m} = R^{5/2}$$

$$\sqrt[2/5]{\frac{Q_p}{Q_m}} = R$$

This relationship states that the discharge capacity of the prototype is related to that of the model by the five-halves power of the ratio between their lineal dimensions. Conversely, with the required capacity of the prototype known, the needed dimensions may be computed by taking the two-fifths power of the ratio between the flume capacity and model capacity. This gives the ratio between lineal dimensions. Applying this ratio to the model dimensions gives the floor width, depth, and length of the desired flume and the necessary radius of curvature of the cylinder quadrant transition.

The use of prototype-model relationships and results from the present study to design a needed field flume for gaging mountain streams may be clarified by a specific example:

> From field observations on a natural channel it is estimated that a flume of 90 c.f.s. capacity will be required to safely hold the peak discharges. At the site chosen for the flume, the channel cross-section is such that a flume with side-wall slopes of about 25° appears to require the least excavation and channel disturbance. The channel slope is 7 percent; thus, a flume channel slope of 4 percent is indicated.
>
> Reference to the surface profile curves of fig. 10 for side-wall slopes of 25°10' and channel grade of 3.9 percent gives the information that at a discharge of 3.02 c.f.s. the depth of flow at the flume entrance is 0.66 foot. The required capacity of 90 c.f.s. is approximately 30 times the flow of the model flume at this depth of 0.66 foot. The two-fifths power of 30 rounds off to 3.90 and is the required ratio between the lineal dimensions of the prototype and the model.
>
> The floor width of the model is 0.33 foot; its depth to hold a flow of 3.00 c.f.s. is 0.66 foot; its length is 32 inches or 2.67 feet; the radius of curvature of the entrance section is 8 inches or 0.67 foot. Applying the factor of 3.90 to these dimensions gives the following specifications for the required flume: floor width, 1.29 feet; depth, 2.57 feet; length, 10.41 feet; radius of curvature of the cylinder quadrant transition, 2.61 feet.

When these dimensions are tried on the natural channel, it may appear that a somewhat different side-wall slope with its accompanying change in flume depth would better fit the natural channel. If so, the calculations can be repeated with interpolations made between the surface profile curves as necessary.

It should also be possible to change the cross-sectional dimensions of the flume disproportionately without getting unsatisfactory flow characteristics. For example, the floor width might be increased at the expense of flume depth for the sake of better fitting the channel under consideration. Referring to the previous illustration, it might be desirable to have a 2-foot floor width instead of 1.29 feet while keeping the depth of 2.57 feet. In this case the capacity of the flume would be increased only proportionately to the increase in cross-sectional area.

This increase may be computed by means of the formula $a = y\,w + \frac{y}{\tan \theta}$ where

a = cross-sectional area
y = depth of cross section
w = bottom or floor width
θ = angle between the side-wall and the horizontal

substituting

$y = 2.57$
$w = 1.29$
$\theta = 25°10'$

gives the area

$a = 17.37$ square feet,

If, as proposed, w is increased to 2 feet, the area then becomes 19.20 square feet. The capacity of the flume with depth of 2.57 would be increased by the ratio of 19.20 to 17.37, or to approximately 100 c.f.s. In this case of increasing capacity, the flume length would not have to be changed since the critical depth point moves downstream only as the depth of flow is increased.

For all lengths of flumes it appears that the piezometer opening may be satisfactorily located anywhere between midlength and one-fourth of the distance from midlength to the flume end. A piezometer opening on each side of the flume but leading together to the same stilling well is advisable. Such an arrangement tends strongly to correct for any stage differences across the flume in the plane of the piezometer openings.

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